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Femtosecond laser interaction with energetic materials

E. Roos, J Benterou, R. Lee, F. Roeske, and B. Stuart

**Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94550 USA
(925) 423-2175, E-Mail roos2@llnl.gov**

Abstract

Femtosecond laser ablation shows promise in machining energetic materials into desired shapes with minimal thermal and mechanical effects to the remaining material. We will discuss the physical effects associated with machining energetic materials and assemblies containing energetic materials, based on experimental results.

Interaction of ultra-short laser pulses with matter will produce high temperature plasma at high-pressure which results in the ablation of material. In the case of energetic material, which includes high explosives, propellants and pyrotechnics, this ablation process must be accomplished without coupling energy into the energetic material. Experiments were conducted in order to characterize and better understand the phenomena of femtosecond laser pulse ablation on a variety of explosives and propellants. Experimental data will be presented for laser fluence thresholds, machining rates, cutting depths and surface quality of the cuts.

Keywords: Laser ablations, femtosecond lasers, explosives and propellants

Introduction

Laser machining of energetic materials and assemblies containing energetic materials is of interest to the scientific and engineering community. The application of laser machining of energetic materials is for the fabrication of new components for test or production and for the disassembly of existing ordnance systems for surveillance or dismantlement. Energetic materials are defined as chemical compounds, which contain both fuel and oxidizer, which react in a short time frame and release a pulse of energy. Examples of energetic materials are high explosives, propellants and pyrotechnics. Energetic materials are thermally, mechanically, and in some case electrostatic, sensitive. Some by-products may be environmentally sensitive. In some cases, material properties have changed with age affecting the sensitive and stability of the energetic material.

Ablation of energetic materials by femtosecond laser pulses is an attractive alternative to conventional machining [1, 2]. Absorption of these ultra-short pulses occurs on such a short time scale that the material is ablated with virtually no heat transfer to the surrounding material [3] resulting in a “cold” laser cutting process and hence, a safe process. In contrast, laser cutting techniques that use laser pulses longer than ~10ps, melt the material and some of the material is vaporized. The rest of the material is blown away with an air stream or re-condenses. There is an amount of slag and re-condensed material deposited on the surface of the material being cut. This deposited material may result in contamination of the starting material. This paper will also discuss femtosecond laser machining of assemblies containing energetic materials, where the energetic materials is in direct contact with metals and dielectrics.

Experimental samples and set-up

Several energetic materials were chosen for machining with the femtosecond laser. In the high explosive (HE) category there are several ways the material is configured such as pressed, melt cased and plastic bonded explosives (PBX). For propellants we consider two types: double base and composite materials. To date we have not fs laser cut pyrotechnic material. Table I is a list of some key properties of typical high explosives. As this table shows, HE has a poor thermal conductivity, therefore heat that is coupled into the material will not be dissipated quickly. Table II lists the materials we machined with the femtosecond laser, which will be presented in this paper.

Energetic material	LX-14	Comp B	Lead Azide	PETN
Color	White/Blue	Brown	White	White
Physical state	Solid	Putty-like solid	Solid	solid
Density (g/cm ³)	1.83	1.58-1.62	4.3	1.78
Refractive index	1.578-1.6	1.578-1.6	0	1.551
Melting point (°C)	270	79-80	Decomposition 345	140
Thermal conductivity (10 ⁻⁴ cal/cm-sec-°C)	10.42	5.23		
Coefficient of thermal expansion (μcm/cm-°C)	55.8	97.5	76.9, 3.4, & 18.3	76.5

Table I Mechanical properties of HE

Material ID	Description	Energetic Material	Comments	Results
High Explosives				
PBX-9407	RDX/binder	HE	PBX	Cut easily at low laser fluence
LX-14	HMX/binder	HE	PBX	Cut easily at low laser fluence
LX-15	HNS/binder	HE	PBX	Cut with some minor problems
LX-16	PETN/binder	HE	PBX	Cut easily at low laser power
LX-17	TATB/binder	HE	PBX	Cut easily at low laser fluence
TNT	TNT	HE	Melt cast	Cut easily, low laser power, melting
Comp B	RDX and TNT	HE	Pressed or melt cast	Cut easily at low laser power, melting
Detonators				
	PETN	Secondary explosive	Secondary HE	Cut easily at low laser fluence
	Lead Azide	Primary explosive	Primary HE	Material detonates when ablated by fs laser
	Lead Styphnate	Primary explosive	Primary HE	Material detonates when ablated by fs laser
Propellants				
PS-1	AP and Aluminum	Composite propellant	Rocket propellant	Cut easily at low laser power, thermally sensitive
HPC-45	Nitrocellulose-Nitroglycerine	Double base propellant	Gun propellant	Cut easily at low laser power, thermally sensitive

Table II - Is a list of the energetic materials, which were laser, cut

Laser ablation experiments were performed on energetic materials with a Lawrence-Livermore-National-Laboratory-developed, breadboard femtosecond laser. TABLE III gives specification for the LLNL laser and Figure I shows a cartoon and layout drawing of the laser of the femtosecond laser.

Specification	Value
Laser medium	Ti:Sapphire
Optical wave length	810 nm
Pulse rate	3500 pps
Pulse width	150 fs
Average laser power	3.5 watts
Laser energy	1 mj/pules
Beam diameter	12 mm

Table III – Laser performance specification

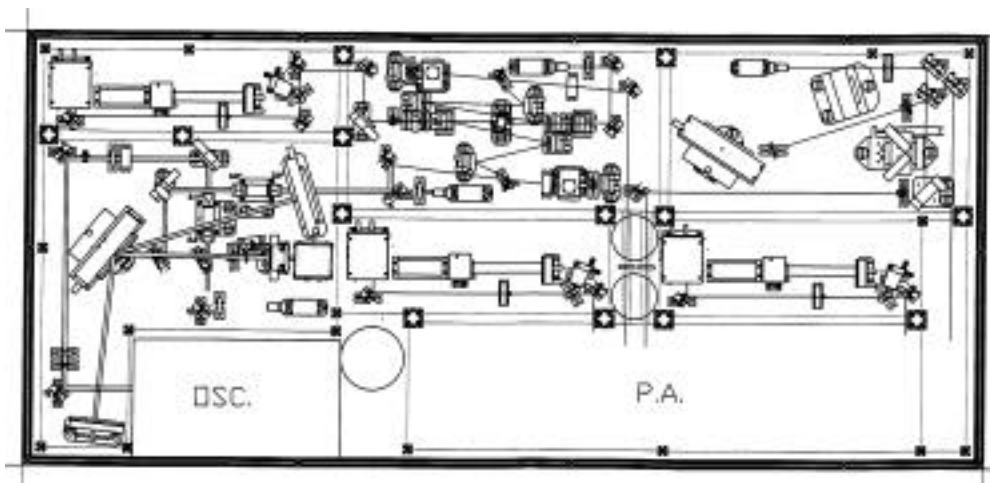
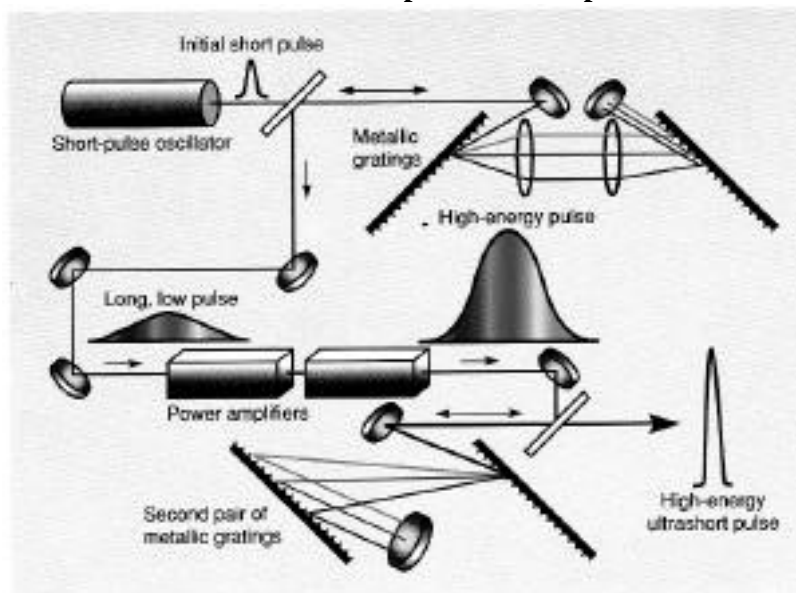


Figure I – Cartoon and a layout of the fs laser

Laser cutting of energetic material was performed in vacuum or at atmospheric pressure within a tank. The tank was designed to contain the pressure pulse, fragments, and heat resulting from a detonation or deflagration. Figure II is a photo of the experimental set-up of the cutting activity. The tank is equipped with several CCD cameras and an optical spectrometer monitoring the optical emission of the sample being cut. The energetic material test samples were mounted on a 4-axis motion control system, which moves the energetic material sample with respect to the laser beam. The 12 mm diameter laser beam is focused to the desired beam diameter with a single lens, which will produce the desired laser fluence. There is an optional laser beam trepanning system, which produces a circle-cutting pattern.

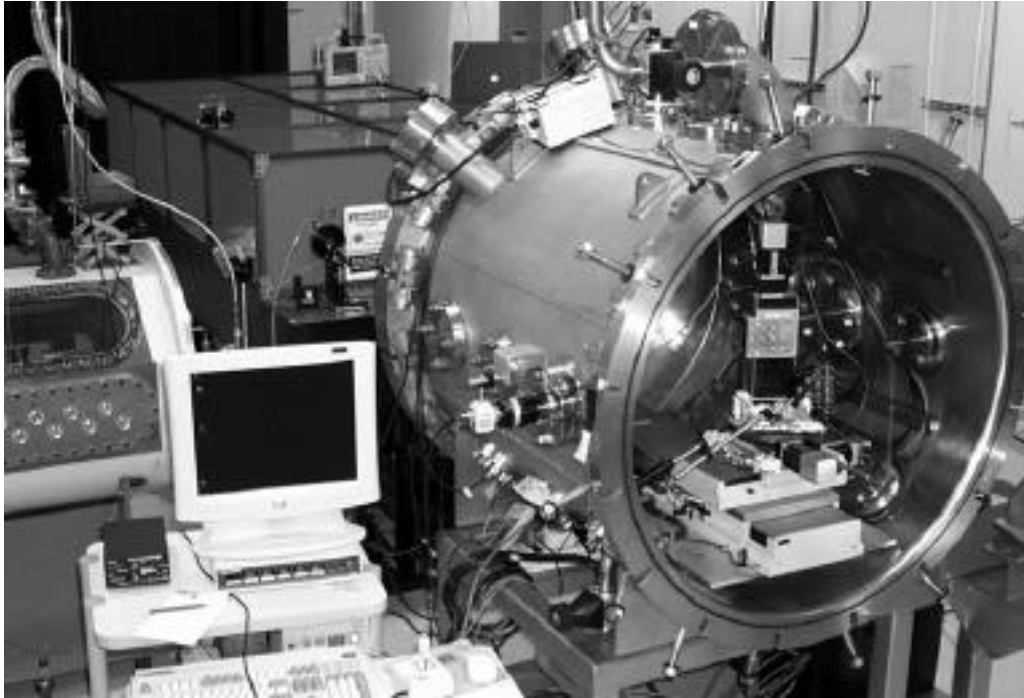


Figure II – Photo of the experimental set-up

Experimental results

Having a laboratory with a femtosecond laser, containment tank and monitor and controls system, we are able to safely perform laser ablation on energetic materials. The objective of the experiments is to obtain quantitative data in the following:

- Establish optimum cutting parameters for energetic materials and ordnance systems.
- Establish machining rates for various materials and process.
- Find safety limits for various explosives, which allow us to safely cut into energetic material without detonation or deflagration.
- Establish size, material or geometry limits.
- Physical changes in the material, such as surface quality, particle size, and loss of binder and changes in density or formation of voids.
- Have the energetic properties of the material been affected?

We have established the cutting parameters for all energetic materials named in table 1. The key parameter, laser fluence, was found to be optimal at 1 to 4 J/cm² for the energetic materials listed in table I. This is in agreement with laser ablation of dielectric materials [3, 4 & 5]. Laser fluence above these levels dose not increase cutting rates and roughens the laser ablated surface, which may result in heating

the high explosives. Several experiments were performed to determine the effects of cutting deeply into energetic material.

High explosives

The first experiments were to cut slots 6 to 12 mm deep through high explosive material, clean up the laser cut and inspect the HE material. Figure 3 shows magnified and enhanced optical photographs of three materials, LX-14, LX-17 and CompB. These photographs show that the size and shape of the crystals of high explosive have not been modified, the presence of the binder, and the absence of voids. The optical inspection is in agreement with standard material showing that the crystal size and presence of binder and density of material has not noticeably changed.

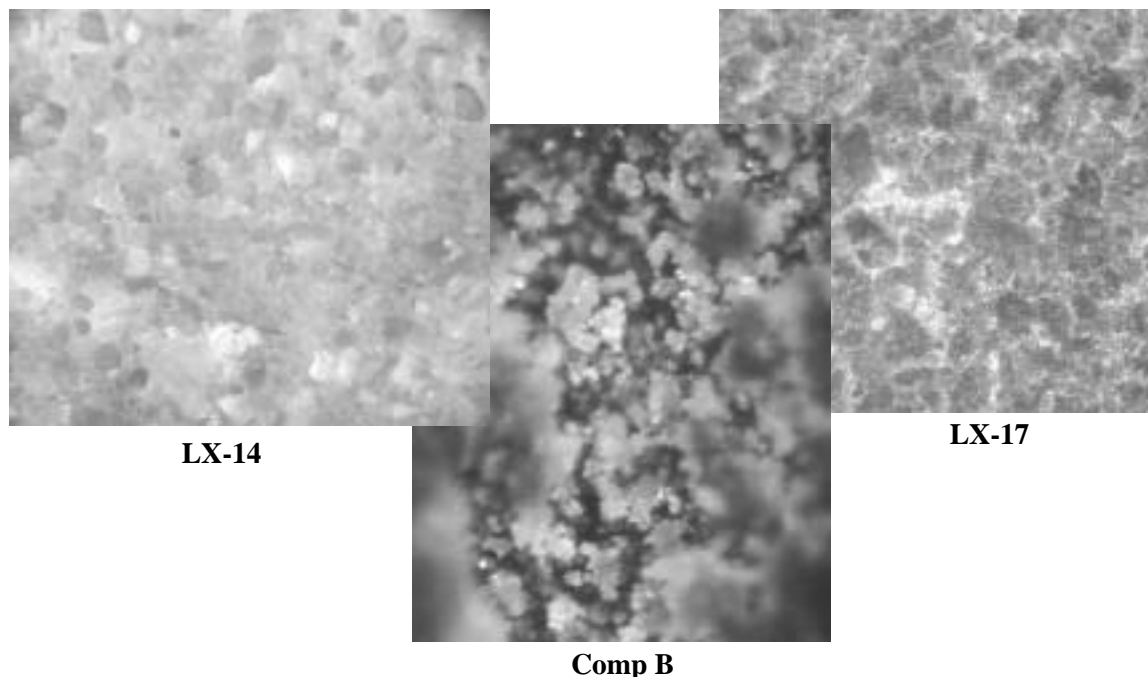
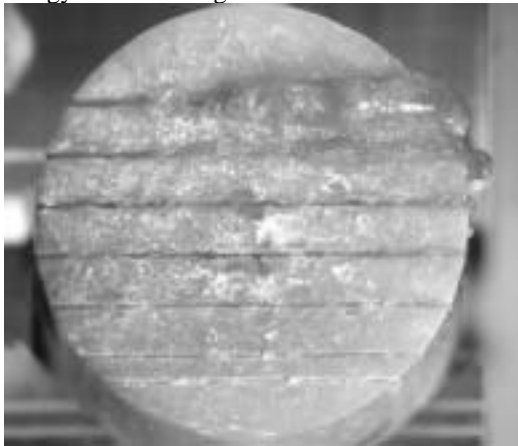


Figure 3 – Photo of femtosecond-laser cut surfaces of high explosive material

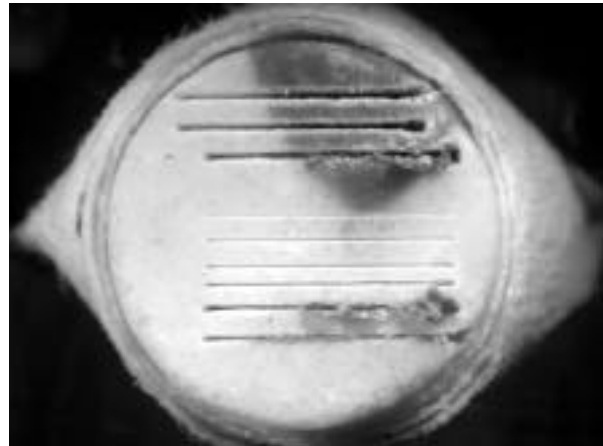
Femtosecond laser cutting is advertised as cold cutting, meaning that there is little heat deposited in the ablation process. This is true but when cutting deeply into material, the laser beam may dwell in a position for a period of time or large angle scattering may be reflected and couple some of the laser energy into the material being ablated. Figure 4 shows photographs of high explosives cut at a laser fluence of $\sim 2\text{J}/\text{cm}^2$ and a laser beam movement of 4mm/min. Under these conditions there were around 1000 laser pulses in a displacement of one beam diameter. The Comp B, a material with a melting point of 80°C, shows obvious evidence of melting by the cutting operation. The LX-14 also shows evidence of melting. LX-14 is 95% HMX and 5% estane. HMX melts at 270°C and then goes exothermic, but the binder can melt and flow. We have concluded for safety and efficiency, coupling of laser energy into the high explosives is unacceptable, therefore we need to find an acceptable cutting process. In Figure 5 we show the results of cutting performed as in Figure 4 but, the laser beam motion was increased to 40mm/min and the number of passes was increased by 10 times. Therefore the total number of laser pulses remain the same. Figure 5 shows no evidence of melting.

Most laser ablation is performed in a vacuum or in controlled atmospheric conditions. The effects of laser ablation in non-vacuum conditions can noticeably affect the results of laser ablation [6]. All of the laser ablation presented in this paper was performed in air and under standard pressure and temperature conditions. Effects due to ionization of the gas medium, including plasma defocusing, self-phase modulation and cooling of the plasma are

present in an air atmosphere. Femtosecond laser ablation of Comp B in a vacuum did not display evidence of melting. It is our belief that the melting occurs by the heating of the air in front of the energetic materials. The laser beam is defocused and distorted, producing an increased spot size resulting in low laser fluence and coupling of laser energy into the energetic materials.

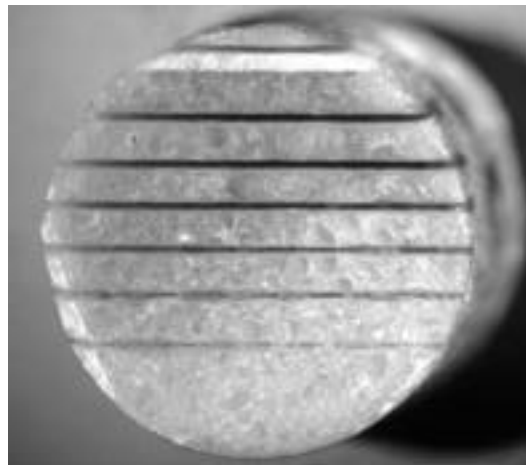


Comp B



LX-14

Figure 4 – Photo of a cut with a fs laser of high explosive and the material melts



LX-14 without heating

Figure 5 – Photo of a cut with a fs laser of high explosive without melting

Detonators

Detonators used in explosive systems are a sub-system of the initiation system, which consists of a firing system, a detonator material and a booster material. The initiation system varies in design from low-voltage hot wire systems to exploding bridge wire (EBW) and slapper systems. The detonator high explosive is of two types, primary and secondary high explosives. Booster material is high explosive used to apply additional explosive energy used to detonate the main explosive charge. The first detonator experiment was the sectioning a hemispherical (hemi) detonator. The hemi detonator had a 0.5-inch diameter and was enclosed in aluminum housing with a plastic base where the bridgewire is located. Figure 6 is a graphic of the detonator assembly. The thin aluminum shell was cut off the plastic header with the fs laser exposing the PBX-9407. The PBX-9407 was ablated exposing the PETN detonator material. Figure 7 shows hemi detonators, which were fs laser ablated to 5 different thickness of HE. The HE column varied from 0.75 mm to 4.0 mm. Close inspection of the surface quality of the PBX-9407 and PETN

show that the femtosecond laser cutting process did not modify the HE material properties. This is a noteworthy accomplishment, since the PETN is pressed to half density, making the material sensitive to external energy sources. For example the PETN can easily fall out or its density can be changed by heat or pressure.

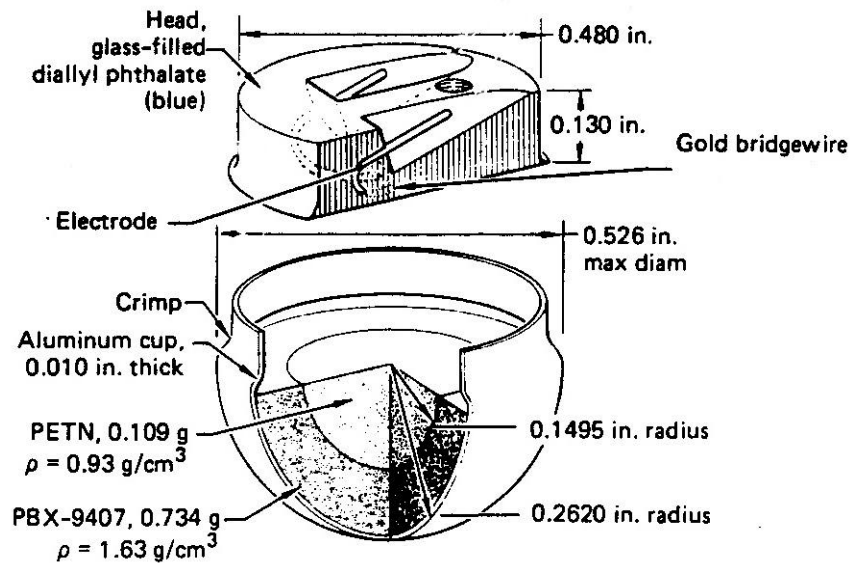


Figure 6 – Drawing of the detonator assemble



Side view of detonators



Top view of detonators

Figure 7 – Hemispherical detonators cut by femtosecond laser

In another experiment on detonators, laser ablation was attempted on assemblies containing lead azide and lead styphnate. The lead azide and lead styphnate were pressed into stainless steel cylinders enclosed on all sides but one. When we attempted to cut through the SS into the HE, both lead azide and

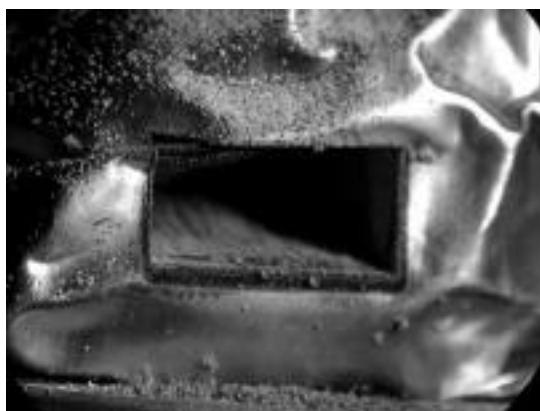
lead styphnate detonated. Detonation occurs immediately when the beam impinges directly on the HE. We were successful in cutting through the SS to within less than 1 mm on the lead azide or lead styphnate without detonation. This experiment was performed to determine whether the source of the detonation was charge produced in the cutting process or hot metal particles from the cutting process. At present we are leaning towards the hot metal particles.

Propellant

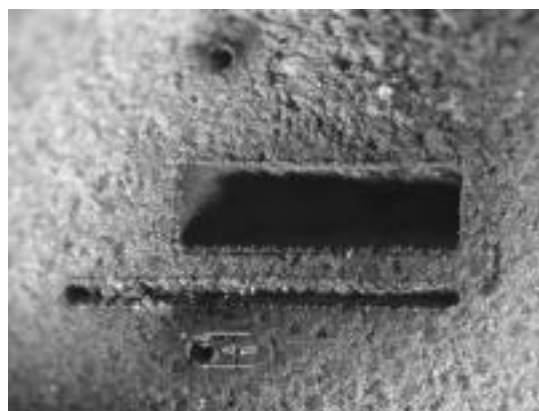
Propellants are used in guns, air bags, fireworks, and missiles. Two types of propellants were chosen; a composite propellant material called PS-1 and double base material called HPT-45. The PS-1 has a fuel of aluminum and an oxidizer of ammonium perchlorate, while the HPC-45 is a nitrocellulose-nitroglycerine based material.

The first laser ablation of propellant was performed on the PS-1. We quickly learned that any heat and or spark source ignited the propellant. The laser beam heating of the surface and a sparks from the laser via air breakdown are potential ignition sources. After several attempts we were able to cut holes, slots and lines in PS-1 without ignition of the propellant. We then wrapped the PS-1 in a triple thickness of aluminum foil and was able to cut through the Al into the propellant without ignition. It should be noted that throwing hot metal particles onto the propellant often ignites propellants. Figure 8 shows a photo of PS-1 ablated with a femtosecond laser.

We performed similar experiments on the HPC-45 and were able to ablate the gun propellant without initiation.



Propellant with an Al cover



**Propellant with laser cut with
Holes, lines and slots**

Figure 8 – PS-1 rocket propellant cut with a femtosecond laser

Conclusions

We have shown that the application of femtosecond laser ablation of energetic materials is promising. The ultrashort pulse lasers can safely ablate energetic materials without effecting the remaining material. This application is a useful tool for demilitarization, surveillance and the creation of new ordnance components. Femtosecond laser cutting is expected to be a technique that can be used to disassemble munitions that are difficult to disassemble by other means without safety concerns or the generation of an unacceptable waste stream. The clean, precision cut made by the femtosecond laser makes it an attractive candidate for many surveillance operations. Finally, novel new shapes of explosives, which can be cut with relative ease with the femtosecond laser, will make possible the development of new energetic components.

The work to date has proven the viability of the ultra-short, high-powered laser-cutting technique for cutting energetic materials. The femtosecond laser is located near a energetic material containment tank capable of handling 10 kg, which allows for the cutting of large HE assemblies and actual ordnance. Thus the femtosecond lab will serve not only to develop the science and applications of femtosecond cutting of explosives but also to serve as a testbed for full-scale mock-up or actual ordinance items.

Acknowledgment

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